Near Sun Ranging

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Near superior solar conjunction, radiowaves traveling between Earth and a spacecraft graze the sun. Ranging, or determining the round-trip radio signal propogation time, provides measurements of signal delay induced by the solar corona and gravity field. This article describes techniques which enhance range data quality during the harsh signal conditions existing at solar conjunction.

I. Introduction

During superior solar conjunction, the line of sight between the Earth and a spacecraft passes near the sun. Radio signals traveling between the Earth and spacecraft pass through and are perturbed by the solar corona and gravity field. Measurements of the round-trip propagation time of these signals can be used to determine the density of the solar coronal plasma and to test theories of relativity. Unfortunately the harsh signal conditions at solar conjunction hinder the ranging systems making the measurements.

This article discusses the special techniques required for successfully obtaining range data when the signal raypath intersects the solar corona. As an introduction to this subject, Section II is a brief description of DSN ranging equipment while Section III describes the sun's effect on the signals to be processed. The reader familiar with ranging may skip either of these sections without loss of continuity. Section IV describes techniques to overcome the signal degradation at solar conjunction. The last section, V, presents some of the Viking results achieved through these techniques.

II. The Equipment — An Overview

DSN Ranging currently employs the binary sequential technique first described by Goldstein (Ref. 1). A detailed description of this technique may be found in Reference 2. The brief description that follows is presented to facilitate reading of this article.

Range from a DSN tracking station to a spacecraft is measured by means of a ranging signal or code consisting of a series of coherently related squarewaves phase modulated onto a S-band carrier. The resulting signal is transmitted from the tracking station to the spacecraft where the ranging signal is coherently detected and remodulated onto a different but frequency coherent S-Band carrier and also, in the case of spacecraft such as Viking, a frequency coherent X-Band carrier for transmission back to earth. Due to the round-trip propagation time a phase offset will exist at the tracking station between the transmitted and received range codes. This offset translates into a measure of range. The periods of the different squarewaves or codes in the series are binary multiples of each other. Range measurement precision is established by the shortest period code used while the longest period limits the ambiguity with which the range is measured.

In the absence of relative motion between the spacecraft and tracking station, the phase offset between the transmitted and received range codes could be measured by direct cross-correlation. Motion of the Earth and spacecraft causes a frequency change, or Doppler shift, in the received signal precluding such direct correlation. A local model of the received signal is therefore constructed by generating a range code which is phase and frequency locked to the transmitted code until some time, designated $T\emptyset$. At $T\emptyset$, the frequency of the local model is modified by an amount equivalent to the Doppler shift. The range measurement is now obtained by determining the phase difference between the local model and received code. This phase offset represents the backward-looking time-of-flight existing at time $T\emptyset$.

III. The Sun's Influence on Ranging

The solar corona and gravitational field perturb the measurement of spacecraft range. Solar influence on ranging is characterized by three effects: interaction of radio waves and the solar plasma, direct reception of the sun's microwave emissions, and relativistic propagation delay induced by gravity.

The solar corona is a plasma whose density is inversely proportional to radial distance from the sun's center. According to Tyler, et al. (Ref. 4), the coronal plasma density may be modeled by:

$$N_e = \left[\frac{2.99}{\rho^{16}} + \frac{1.55}{\rho^{6}} \times 10^{14} + \frac{3.44}{\rho^{2}} \times 10^{11}\right] \times \left[\cos^2\theta + \frac{1}{64}\sin^2\theta\right]^{\frac{1}{2}} \tag{1}$$

where

N_e is in electrons/m^3
ρ is radial distance in solar radii
θ is the solar latitude

Given a $1/\rho^6$ dependence far from the sun and $1/\rho^{16}$ near the sun, plasma effects grow enormously as the sun is approached.

Plasma in the solar corona distorts the velocities of radiowaves. The predominant effect is an increase in the signal's phase velocity and a corresponding decrease in the signal's group velocity. In a tenuous plasma the phase and group velocities, respectively V_p and V_g, are given approximately by (Ref. 3):

$$V_p = c\left(1 + \frac{1}{2}\frac{\omega_p^2}{\omega^2}\right) \tag{2a}$$

$$V_g = c\left(1 - \frac{1}{2}\frac{\omega_p^2}{\omega^2}\right) \tag{2b}$$

where

$\omega \gg \omega_p$

ω_p is the plasma frequency, a term proportional to plasma density
ω is the carrier frequency
c is the speed of light in a vacuum

Because the range code propagates at the group velocity, the increase in range delay due to the corona is inversely proportional to the square of the carrier frequency. This dependence of range delay on frequency provides an important mechanism for measuring the electron density in the ray-path. For example, the Viking spacecraft radio system generates S- and X-band downlink (spacecraft to earth) carriers by multiplying the received uplink (earth to spacecraft) carrier frequency by 240/221 and (11/3) X (240/221), respectively. The difference between the S- and X-band range delays can be converted to measured downlink integrated columnar electron density by (derived from Ref. 3):

$$I_D = \frac{\Delta sx\, f^2\, G^2\, c}{2A}\;\frac{1}{1 - (3/11)^2}\ \text{electrons/m}^2 \tag{3}$$

where

$c = 2.998 \times 10^8$ m/sec
$f \approx 2.112 \times 10^9$Hz uplink carrier frequency
G = 240/221 Transponder S-band ratio
A = 20.15 Conversion Constant
Δsx = S-X Range in seconds

The determination of I_D provides a means for separating plasma induced delay from range delay measurements. I_D is also converted, through additional analysis, into N_e, the measure of electron density, for comparison against solar models such as (1) above.

Plasma dynamics or turbulence causes scintillation of traversing radiowaves, which is manifested as broadening of the signal carrier spectrum. The tracking station and spacecraft receivers must therefore contend with both degraded carrier signal-to-noise ratio and randomly gyrating carrier frequency. Since the downlink S- and X-band carrier frequencies are derived from the uplink received carrier, the downlink jitter has two components, the scintillation encountered during downlink propagation and the uplink jitter multiplied by 240/221 and S-band and (11/3) X (240/221) on X-band. The magnitude of the scintillation effect appears to be proportional to $1/\rho^{1.5}$ far from the sun and $1/\rho^{3.5}$ near the sun (Ref. 5). From practical experience, scintillation sets the minimum sun-earth-probe-angle limit at which ranging can be accomplished.

The sun is also a powerful microwave emitter and can increase a tracking station's noise temperature. Using an empirical technique, S. T. Rockwell derived a formula for the degradation in signal to noise ratio due to front end noise temperature (Ref. 6):

$$\Delta \text{ SNR(db)} = 10 \log \frac{\left[(T_Z + T_{EL})^2 + T_{SUN}^2\right]^{\frac{1}{2}}}{T_Z + T_{EL}}$$

where

T_Z = noise temperature with antenna at zenith (measured)

$T_{EL} = 25.9e^{-.066(EL)}$ for 64m station where EL is elevation in degrees

$T_{SUN} = 6.1 \exp\,[5.2/(\text{SEP} + .34)]$

where SEP is sun-earth-probe angle in degrees.

This model is apparently a good approximation at SEP's greater than about 1.5°. Within 1.5°, disturbances in the antenna radiation pattern – known as quadrupod effects – can cause significant error in the term T_{SUN}. Whenever the sun appears in one of the sidelobes caused by an antenna's quadrupod structure, the system noise temperature will become much larger than T_{SUN} predicts.

IV. Operations

In the previous section, the modelable plasma/solar effects were discussed. The variations in these effects are difficult or impossible to model. It has been stated that the mean and σ of any measurement of coronal density are the same (Ref. 5). Under such dynamic conditions, only real-time monitoring can assure optimal range data return. Therefore, this section is devoted to the operations required to optimize near-sun ranging.

A. Station Optimization

The least sophisticated method to overcome low signal-to-noise ratios is to use as much power as possible in the signal. During the Viking superior solar conjunction 100 Kw was the typical DSN transmitter power. Use of high power improves overall system performance and assures that the spacecraft receiver stays in lock.

Another "obvious" technique is to avoid ranging during periods of maximum quadrupod effect. Programs exist (Ref. 7) which when given spacecraft, sun, and tracking station geometries compute front-end noise temperature as a function of time. During Viking for instance, plots of noise temperature were used to plan Lander ranging times. Because the Lander transponders were limited to operational periods as short as 15 minutes, such planning was vital to the success of the conjunction experiments.

Apparent carrier frequency spread due to scintillation, as well as degraded SNR, combine to cause the DSN receiver to "drop lock" and slip cycles. A large static phase error (SPE) in the receiver's phase-locked-loop will cause these slips to be in only one direction. Because the ranging system is "Doppler rate-aided", the result, at best, is an erroneous drift in range derived measurements of plasma variation and, at worst, is a loss of ranging due to smearing of the code. If the SPE is kept near zero, the slips occur with equal probability in either direction and become equivalent to random noise. The SPE is maintained near zero by using a Programmed Local Oscillator (PLO), driven by predicts, to track the spacecraft signal within the receiver pass-band. An alternative is to approximate the predicts with ramps generated by the Block IV receiver's Programmed Oscillator Control Assembly (POCA).

Carrier scintillation must also be compensated by adjusting the receiver carrier loop bandwidth. The 10 Hz bandwidth normally used for tracking is inappropriate when the carrier is spread over 100 Hz. A wider bandwidth can, however, degrade an already poor SNR. The optimum setting can be based on spectral broadening measurements.

B. Ranging System Optimization

Ranging yield can be improved through the use of multiple range acquisitions. When operating near the sun, the success probability of any particular acquisition is low. If the acquisition time is short, random noise alone limits the success probability. If the acquisition time is increased to combat the additive noise, receiver cycle slips distort the local reference code through the doppler rate-aiding mechanism and severely corrupt the range measurement. As noted above, the interference from the sun is highly dynamic, and may be quiet one moment and severe the next. In practice the acquisition time is set to a compromise value and pipelining used to increase the number of acquisition attempts and hence the chance of at least one successful acquisition during the pass. Multiple measurements at a time of large uncertainties also confirm system operation and increase confidence in the data obtained.

During solar conjunction, the apparent modulation phase jitter can exceed the period of the usual 2 μsec high frequency range code. Hence a code of larger period must be used to prevent loss of data. The Mu-II Ranging System can use any code from 8 MHz to 2 Hz as a first code. Initial codes as long as 32 μsec were used for the Viking conjunction. A longer initial code minimizes the number of components, thereby minimizing the chance of a component error within an acquisition.

Short term variations in the coronal plasma can be observed by monitoring the resulting phase changes of the returned range code. Because the highest frequency code allows the most accurate measurements of these changes, the highest frequency code is sometimes mixed with the lower frequency components of the range acquisition sequence. Its phase offset is thereby continuously measured.

Near the sun this practice becomes a liability. Combining two range codes splits the available power between them and complicates cross-correlation of the received range code against the local model. The effect is to decrease the probability of correctly measuring the phase of the lower frequency code thus jeopardizing acquisition success. The Mu-II is normally operated during solar conjunction with code mixing disabled during the acquisition.

C. Post-processing

Non-real time processing can be used to both improve and verify the quality of range data. The more general of these techniques is "pseudo-DRVID" (Ref. 8). Applicable to either the Mu-II or Planetary Ranging Assembly (PRA), pseudo-DRVID compares the relative change in spacecraft range indicated by successive range points to the change measured by the integrated Doppler cycle count. The degree of agreement is good evidence of the reliability of the range data.

Beyond verification, range data can actually be improved through the use of a maximum likelihood technique. Reference 2 explains that the ranging algorithm used by both the Mu-II and PRA measures the phase of only the highest frequency component of the range acquisition. The contributions of all subsequent components are determined merely from the sign of their inphase correlation voltages. Information contained in the quadrature channel is ignored.

A better algorithm for range determination was described by Erickson and Layland in Reference 9. Their maximum likelihood method treats the phase measurement of each component (within the limits of its ambiguity and resolution) as an independent determination of range. The algorithm uses the Mu-II correlation voltages to reconstruct the correlation function between the local reference code and all possible delays of the received code. Assuming that additive white gaussian noise disturbs the received code, the correlation function can be treated as a likelihood function, e.g., the a posteriori probability of all range values. After accounting for the delays introduced by the Mu-II algorithm's manipulation of the reference code, the likelihood functions of all components are directly added to produce a likelihood function for the range determined by the entire acquisition. The most probable range point is selected at the peak of this combined function. According to Timor in Reference 10, an improvement of up to 1.5 dB in ranging signal-to-noise ratio can be obtained with this technique.

In addition to providing a range number, the maximum likelihood program plots the acquisition likelihood function. With some knowledge of the process, the form and symmetry of this plot can be used as an indicator of range quality. Analysis by this technique offers an additional evaluation tool to the range data user or experimenter.

V. The Results — 1976 Viking Superior Solar Conjunction

The latest use of the techniques espoused here was in support of the 1976 Viking Superior Conjunction Experiments. Both the solar corona and the relativity experiment involved ranging under very adverse conditions. The quality of the range data is reflected in Figure 1 showing electron density, determined by S- and X-band range, plotted versus the ray-path's normal distance from the sun (Ref. 4). Individual points depict 312 independent acquisitions. The solid line is the density predicted by equation (1). Note that the highest data point was derived from a successful Mu-II range acquisition at $\sim .57^\circ$ SEP. The S-X differential was just greater than 61 μsec. This point represents the closest measurement (in terms of SEP) of coronal total columnar electron density ever made.

Viking also afforded the opportunity for the best test to date of Einstein's Theory of General Relativity. The interested reader is directed to Reference 11 for more information. The precision of the Mu-II ranging system was spectacularly demonstrated. Figure 2 shows a linear fit to residuals obtained by differencing range data (corrected for the coronal plasma effect) from predicts generated by Dr. Irwin Shapiro and his associates at MIT (a D.C. bias has been removed). The points are scattered about the line by about 95 nanoseconds. This 15 meter scatter will, hopefully, be improved with more processing. The data does, however, yield a measurement of the relativistic induced delay good to .5% – a two-fold improvement over any previous experiment and a four-fold improvement over any previous test involving a spacecraft.

Figure 3 shows the precision during a single tracking pass. Unfettered with day to day plasma variations and ephemeris errors, the residuals show a scatter of less than 10 nanoseconds. Ten nanoseconds out of a round-trip-light-time of nearly 2500 seconds is equivalent to five parts in 10^{12}, which, according to Dr. Shapiro of MIT, is the most precise measurement of distance yet made (Ref. 12).

The Viking experience does not signal the end of solar conjunction experiments. It is hoped that this paper will serve as a starting point and aid to the ranging experimenters on Voyager and later missions.

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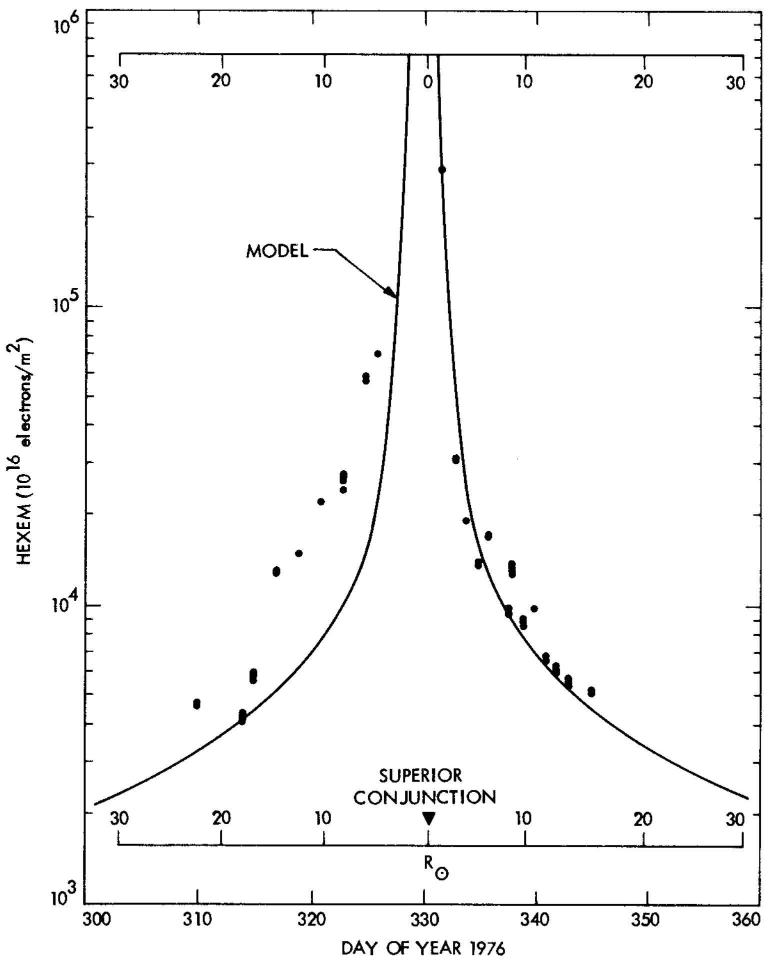

Fig. 1. Integrated electron density measured by Viking S-X range ($R_\odot$ = solar radius)

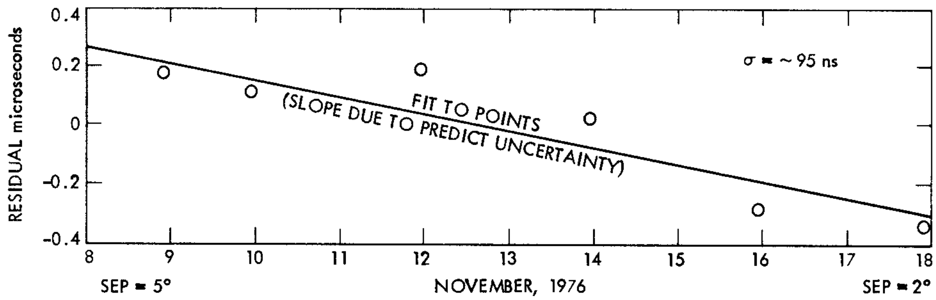

Fig. 2. Inter-day range residuals, Viking Lander 2

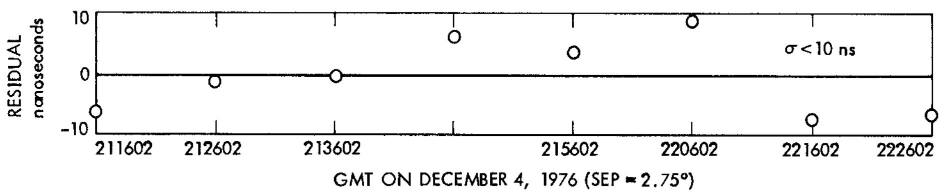

Fig. 3. Intra-day range residuals, Viking Lander 1